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Design and experimental analysis of a thermoelectrically temperature controlled bearing shield for motorised spindles

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Abstract
With the rapid technological advancements in high-tech industries, the demand for components with sub-micrometre geometric and dimensional accuracy is increasing. The thermal behaviour of machine tools is of crucial importance in the high-precision machining of such components. Considerable efforts are made to dissipate the heat generated by machine components such as actuators and motorised spindles. Despite the use of complex water cooling systems, these heat flows lead to elevated temperatures, which in turn result in thermally induced component deformation and thus reduced machining accuracy. Due to their exposed position with direct contact to the workpiece and their speed-dependent thermal load, motorised spindles and their thermal behaviour are of great importance and the subject of intensive research. Thermal stabilization of the front bearings of motorised spindles, even under varying speeds, can stabilize the shaft's thermal deflection.

This study addresses the design, measurement, and control of a thermoelectrically controlled front bearing for a motorised spindle. Here, 40 thermoelectric strips were assembled into a tubular Peltier module that connects the cylindrical surface of the bearing shield to the surrounding water cooling system. A prototype, consisting of the bearing shield, tubular Peltier module, heating coil, temperature sensors, and water cooling system, was used to investigate the thermal behaviour of the bearing shield under various head loads in detail. Different PID (proportional-integral-derivative) control strategies for a Peltier temperature controller were tested using step response measurements. The measurement results of the investigated IMC (internal model control) PID and CHR (Chien-Hrones-Reswick) PID strategies were compared with those of a commercial controller. Depending on the PID parameters and changes in conditions, a temperature stability within a tolerance range of ±0.1 K can be attained in between 8 second for thermal disturbance rejection and 16 seconds for reference tracking.

Temperature regulation; Peltier module; PID Controller; motorised spindle

1. Introduction

Driven by the increasing demand from the high-tech industry for components and parts with geometrical accuracies in the sub-micrometre range, the requirements for machine tool manufacturing are increasing. Besides increasing accuracy through sophisticated control systems and improved machine quality, the thermal behaviour of machine tools and their components significantly influences the achievable machining accuracy [1, 2]. To achieve higher machining accuracy, it is essential to minimize the effects of thermal stresses through suitable cooling concepts. Denkena et al. [3] provide a comprehensive overview of cooling strategies for motorised spindles, distinguishing between passive and active approaches. Passive cooling strategies are primarily based on convective heat transfer to the ambient air, which is typically enhanced by optimizing the heat sink geometry. In contrast, active cooling systems primarily use a flowing cooling medium, such as oil, water or active air flow which is applied in the immediate vicinity to the heat sources [3, 4].

An alternative approach, which serves as the basis for this work, involves the use of Peltier modules. A Peltier module consists of alternating p- and n-doped semiconductor elements positioned between two ceramic plates, electrically connected in series and thermally in parallel. Based on the Peltier effect, first discovered by Peltier [5], a heat flow can be generated in the Peltier module by applying an electric current. The applicability of this method was demonstrated by Fan et al. [6], who attached Peltier modules, combined with a heat conduction sleeve, to the outer surface of the motorised spindle housing.

Uhlmann et al. [7, 8, 9] developed an actively temperature-controlled motorised spindle that employs prismatic Peltier modules integrated within the motorised spindle housing, situated between the water cooling channels and the primary heat sources. Three groups of independently controllable Peltier modules are arranged circumferentially around the front and rear bearings, as well as the stator. This configuration facilitates precise control of the front bearing temperature T_{bearing}, rear bearing temperature, and stator temperature. Using this approach, the warm-up time required to reach the thermal steady state of the axial shaft displacement can be reduced by up to 79 %. To reduce the costs of integrating a thermoelectric temperature control system into motorised spindles, a novel thermoelectric temperature control system based on a tubular Peltier module was developed.

This study presents the thermal characterisation of such a system and the investigation of different proportional-integral-derivative (PID) control strategies for a Peltier temperature controller used in a functional prototype of the front bearing shield of a motorised spindle.

2. Functional prototype

2.1. Design and experimental setup

To investigate the behaviour of a bearing shield and to design a control system for temperature control using thermoelectric modules, a functional prototype was developed based on the bearing shield of a motorised spindle (MFW840/50, FISCHER DEUTSCHLAND GMBH, Langenfeld, Germany). The functional prototype, illustrated in Figure 1, consists of a bearing shield with build-in temperature sensor, a coil tube heating cartridge, a tubular Peltier module, and a water-cooling system. The design is based on the work of Uhlmann [9].

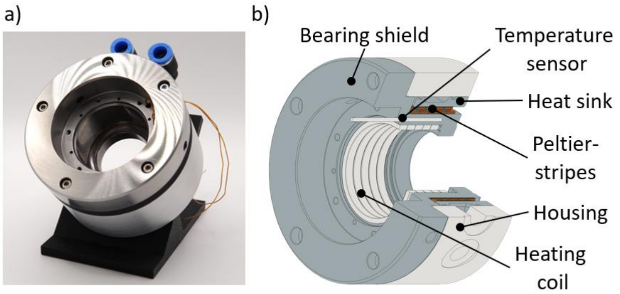

Figure 1: a) Photo of the assembled functional prototype without coil tube heating cartridge. b) Cross-sectional representation of the functional prototype with labelled components.

The tubular Peltier module consists of 40 individual stripes, each containing four pellet pairs made of p- and n-doped thermoelectric material. These Peltier stripes are electrically connected in series through copper bridges. To ensure optimal thermal and mechanical coupling between the bearing shield, the tubular Peltier module, and the heat sink, the thermoelectric stripes were placed to the bearing shield using double-sided adhesive graphite foil, while the heat sink was thermally shrunk onto it. The cooling channel was sealed with two O-rings between the heat sink and the housing, and the housing was subsequently bolted to the bearing shield.

For temperature measurement within the bearing shield, a calibrated PT1000 temperature sensor (TEMPERATUR MESSELEMENTE HETTSTEDT GMBH, Maintal Germany) was utilized. To minimize external influences such as convection and thermal radiation, the functional prototype was insulated both inward and outward. During the experiments, the water cooling was maintained at a constant temperature of 20 °C with a volumetric flow rate of 3.6 l/min.

To demonstrate the performance and temperature stability of the functional prototype, an initial measurement series was conducted to assess the temperature of the bearing shield as a function of the heating power of the heating coil and the Peltier current. The heating power was increased from 30 W to 100 W in increments of 10 W, while the current was raised from 0 A to 6 A. Based on previous measurements, it can be assumed that a heating power of 100 W should cover the heat load of the motorised spindle at a rotation speed of 50.000 1/min. To protect the Peltier module from potential defects during extended measurement campaigns, the current was limited to 6 A and the minimum bearing shield temperature was set to +10 °C. In the motorised spindle, Peltier modules can also be operated at higher currents and lower temperatures for rapid control over short time periods.

2.1. Results

The measurement points shown in Figure 2 represent the temperatures in the bearing shield after reaching thermal steady state. From the measurement at 0 W heating power, it can be inferred that an increase in the heating coil power by 10 W results in a temperature rise of the bearing shield by 4.7 K ± 0.2 K. This increase in temperature can thus be assumed to be linearly dependent on the heating power. Utilising the linear relationship, an extrapolation to 0 W heating power and 0 A Peltier current results in a heating shield temperature of approximately 20 °C, which is equivalent to the cooling water temperature. As the Peltier current increases, the temperature in the bearing shield decreases because heat is pumped from the bearing shield to the coolant via the Peltier effect. Although the heat conduction through the Peltier effect is approximately linear, the decrease in bearing shield temperature is not, as the Joule heat increases quadratically with rising current, which must be additionally dissipated along with the pumped heat. To illustrate this trend, a trend line is drawn at the heating power P_{Heater} = 70 W, see Figure 2.

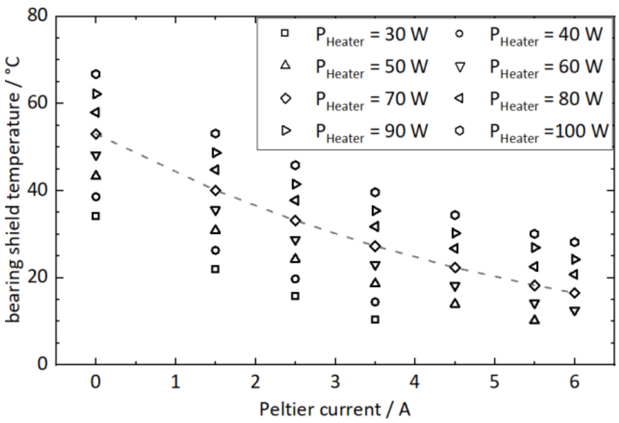

Figure 2: Bearing shield temperatures at different heating powers and Peltier currents.

To quantify the performance of the Peltier module, it can be investigated at which maximum heating power the bearing shield can be cooled to up to a certain temperature. This is a recognized method for determining the maximum current and maximum heat flow for standard Peltier modules [15]. For this purpose, the recorded curves were extrapolated using a second-order polynomial fit.

In the first step, the Peltier currents, required to achieve bearing shield temperatures of 20 °C and 30 °C, can be calculated. These values are summarised in table 1.

Table 1 Required Peltier currents for bearing shield temperatures of 20 °C and 30 °C at different heater powers.

heating power	Peltier current for $T_{bearing}$ = 20 °C	Peltier current for $T_{bearing}$ = 30 °C
30 W	1.81 A	0.48 A
40 W	2.45 A	1.01 A
50 W	3.23 A	1.65 A
60 W	4.08 A	2.32 A
70 W	5.02 A	3.01 A
80 W	6.31 A	3.80 A
90 W	/ n.a. /	4.56 A
100 W	/ n.a. /	5.51 A

As can be seen, the functional prototype cannot achieve a bearing shield temperature of 20 °C with heating powers exceeding 80 W. To determine the maximum cooling power of the Peltier module, the minimum achievable temperatures at the respective heating powers of the heating coil were derived from the extrapolations. These values approximate the maximum cooling capacity of the functional prototype to 89 W at 8.6 A in thermal steady state.

Based on the complete characterization of the system, it can be demonstrated that the cooling capacities required for the operation of the motorised spindle can be adjusted based on the current. Thus, the current can be used as the direct control variable for regulating the temperature of the system.

3. PID controller evaluation

To define control parameters, several methods described in the literature were investigated. The most promising, namely CHR-based [10, 11] and IMC-based [12], were applied, with step tests conducted as presented by Widagdo et al. [10] and Diwakar et al. [13]. The basis for this were the measurements shown in Figure ***2*** at 30 W heating power and 1.5 A Peltier current.

The resulting PID parameters for the CHR-based approach, featuring fast control in response to setpoint changes and a disturbance with 0 % overshoot, as well as the mathematical IMC-based approach for λ values of 3 and 5, are presented in Table 2. Thereby λ is an adjustable parameter that determines the speed of response, increasing λ raises the closed-loop time constant and slows down the speed of response. Conversely, decreasing λ has the opposite effect. λ can be adjusted to compensate for model mismatch in the design of the control system. The higher the value of λ, the greater the robustness of the control system [14].

Table 2 Examined control strategies with derived PID values

	P	I	D
IMC λ 3	2.5109	0.0362	0.4964
IMC λ 5	1.5978	0.0231	0.4964
CHR	5.2348	1.3987	2.6174

These derived control parameters were compared with the auto-tuning feature of the commercially available Peltier controller type PWR CTRL M (Dr. Neumann Peltier Technik GmbH, Neuried, Germany) as a reference. The parameters, defined in table 2, were implemented in a PID controller, running on a modular real-time system Adwin-Pro II (Jäger Computergesteuerte Messtechnik GmbH, Lorsch, Germany).

To assess the capacity of the different PID controllers for reference tracking, the temperature of the functional prototype was regulated to 30 °C using a cooling water temperature of 20 °C, a flow rate of 3.6 l/min, and a heating power of 50 W. After 300 seconds, the setpoint was raised to the bearing shield temperature of 40 °C, and the settling time to reach the target temperature was measured. The settling time is defined as the point in time at which the measurement data first lie within a tolerance range of ±0.1 K of the target temperature and subsequently remain within these limits.

After additional 300 seconds, the system was set back to 30 °C. In addition to the settling time, the overshoot and undershoot is evaluated for each set of PID parameters. After 600 seconds, the power of the heating coil was set to 0 W to simulate a stop of the motorised spindle, and after 900 seconds, it was returned to 50 W to show the behaviour at a restart of the motorised spindle. Figure 3 shows the controlled temperatures during this procedure for all four PID controllers.

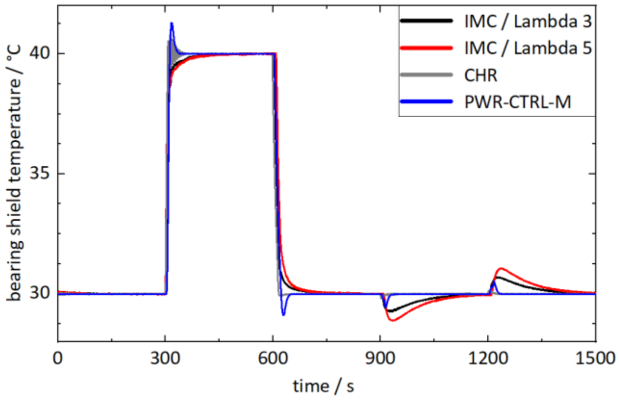

Figure 3: Representation of the complete load cycle of the functional model with changes in the target temperature at 300 and 600 seconds and a simulated engine stop at 900 seconds, followed by restarting at 1200 seconds.

Table 3 presents the settling times of the different PID controllers for individual load changes in the system. 30 °C – 40 °C and 40 °C – 30 °C indicates the rise of in temperature and vice versa, 50 W – 0 W and 0 W – 50 W the change in the heat load of the heating coil.

Table 3: Settling times for different load changes

	30-40°C	40-30°C	50-0 W	0-50 W
IMC λ 3	89 s	100 s	93 s	196 s
IMC λ 5	117 s	123 s	140 s	245 s
CHR	41 s	16 s	8 s	10 s
PWR-CTRL-M	33 s	43 s	24 s	26 s

Figure 4 shows a section of the measurements taken after 300 seconds. It is evident that the auto-tuning feature integrated within the Peltier controller of type PWR-CTRL-M (Dr. Neumann Peltier Technik) provides effective and smooth temperature control, although it exhibits the most significant overshoot in this range. In contrast, the signals derived from the IMC control parameters are noticeably slower during all temperature and load transitions. The CHR parameter set demonstrates a pronounced, nearly critical oscillation but is the fastest controller. With the CHR control parameters and the reference (Dr. Neumann Peltier Technik), temperature stability after changes in head load and target temperature of less than 0.2 K can be achieved within seconds.

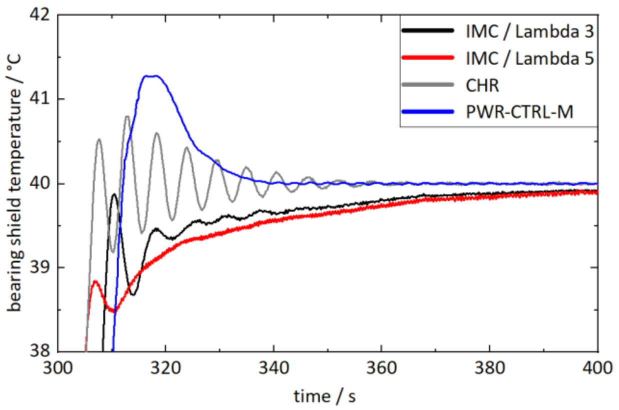

Figure 4: Section of the measurement between 300 and 400 seconds showing the oscillation behaviour of the individual control parameters.

3. Conclusion and future work

This study presents a novel approach to thermoelectric temperature control for the bearing shield of a motorised spindle, along with potential PID parameters for such temperature control.

Using measurements on a functional prototype consisting of a bearing shield, a heating coil, a tubular Peltier module, and a water cooling system, the system has been fully characterized and the influence of heating power and Peltier current on the bearing shield temperature has been determined. A maximum heat load of 89 W at 8,6 A is achievable at thermally steady state.

Different control parameters were examined and the effectiveness of the temperature control and settling time for changing boundary conditions were demonstrated. The regulated operation can achieve a temperature stability of less than 0.2 K. Depending on the PID parameters and changes in conditions, a temperature stability within a tolerance range of ±0.1 K can be attained in between 8 second for thermal disturbance rejection and 16 seconds for reference tracking.

In the future works, the findings presented in this work will be transferred to the control of a thermoelectric motorised spindle. In addition, the control parameters will be extended and validated in further tests to cover the entire range of possible applications for the motorised spindle. Furthermore, bearing shields with different tubular Peltier module configurations will be prepared and characterized.

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